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Sedimentary Dynamics of Windfield-Source-Basin System

New Concept for Interpretation and Prediction

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Foreword I

A stable energy supply system is the material guarantee to realize the Chinese Dream. Currently, the second venture of the China oil and gas industry is ascending rapidly. In this context, the innovation of theory and method on sedimentology, which is a basic and important discipline, will potentially lead to new discoveries in oil and gas energy industries. In recent years, Prof. Zaixing Jiang has been working on sedimentary dynamics, and focusing on the impact of the windfield on subaqueous depositional environments. As an important supplement and improvement of the existing theories of sedimentology, it is expected to become a hot subject in the future sedimentology study. As a writer of the foreward to this book, I was fortunate to get the manuscript and read it through in advance and found the following innovative progresses:

(1) The research on eolian sedimentology is becoming more and more mature, but the influence of wind on aqueous depositional environments and their responses to the depositional process is not well-understood at present. This book raises the concept of “windfield” from the traditional lakes, oceans and transition depositional environments, and emphasizes its interaction with the source and basin, as well as their dynamical control on most of the sedimentary systems, including the formation and distribution of clastic and carbonate rocks.
(2) Quantitative study on sedimentology is considered as the basic direction during the sedimentology development, however, the quantitative study of paleowindfield, as described in the beginning of this book is rare in the previous research. The quantitative reconstruction methods on paleo-wind also fill the blank of atmospheric circulation in paleoclimatology.
(3) Oil and gas exploration is an important battlefield for sedimentology application, and this book shows examples of windfield-source-basin system and its constraints and influences on the source, reservoir and cap rocks, as well as their combinations in petroliferous basin, providing a new perspective for petroleum geology evaluation.
(4) The book is rich in content, including the results of modern outcrops study, such as the Qinghai Lake, and the deeply buried subsurface deposits, such as the thousands of meters deep deposits in the Shengli Oilfield, the Liaohe Oilfield and the Huabei Oilfield covering different types of sediments in Mesozoic-Cenozoic. Besides, geology, geophysics, hydrology, meteorology and other disciplines are intersected, representing the scientific connotation of “system”.

As Prof. Zaixing Jiang’s peer researcher, I have been paying attention to his academic achievements over years. He has been leading his team and devoting themselves into the study of sedimentology for decades and published abundant high-quality papers. This book represents the continuous, hard work and innovative results by his team and himself. I would like to recommend this book to every peer researcher on sedimentology and petroleum geology.

May 2016

Yongsheng Ma
Academician of Chinese Academy of Engineering
Sinopec Group

Foreword II

China is a country of great oil and natural gas production and consumption and has increasing demand for energy recently. Although oil and gas resources are relatively rich, it is still difficult to meet the needs of sustained and rapid development of the national economy, which leads to strong contradiction between the supply and demand of oil and gas. In addition, the major petroliferous basins in China are gradually entered into the high-level explored stage. The onshore oil and gas exploration is mainly targeted on the lithologic oil-gas reservoir, which is subtle and more difficult to explore. Especially for the mature oil and gas exploration area in the eastern basins, the oil and gas reservation and production are not stable and the new areas and new types of oil and gas reservoirs are hard to find. Facing the grim situation and increasingly complex exploration targets, how to expand new field of exploration, broaden new horizons of development of oil and gas, and make new breakthrough for newly discovered oil and gas exploration by further study on petroleum geology and new technical method, are not only major issues to the geologists and petroleum explorationists, but also challenges and opportunities to China's petroleum geology theory and exploration.

The new scientific findings are commonly from the first-hand information from the field work, and the new ideas of exploration are normally from the practice of oil production. It is the new scientific discoveries and new exploring ideas together that promotes the formation of new theories of petroleum geology and exploration, which guides the development of oil and gas exploration. During the long-term research on the sedimentology of petroliferous basins in eastern China, Prof. Zaixing Jiang and his team combine the natural phenomena of "winds spring-up water" with the sand body prediction technique. They proposed the concept of windfield-source-basin system sedimentary dynamics which is original, will guide explanations and distribution prediction of depositional systems.

The book windfield-source-basin sedimentary dynamics points out that the depositional processes is closely related to the wind/climate, source, and basin system, thus involving controlling elements such as paleoclimate, paleo-provenance, palaeogeomorphy, and palaeo-water depth. The windfield and the associated paleoclimate control the internal sedimentary structures and textures of sediments; the provenance is the material basis; and the palaeogeomorphy and paleo-water depth significantly affect the distribution and scale of sedimentary bodies. These factors, with each one being constrained by the other, are changing constantly and interact with its counterparts to influence the depositional system. The windfield-source-basin system sedimentary dynamics research is aimed to explore how these factors control sedimentary processes.

At first, this book introduces the development of depositional system theory in the previous 100 years, focuses on the multi-controlling factors of depositional systems distribution, and suggests that the windfield is an important parameter in the concept of windfield-source-basin system sedimentary dynamics. This book also illustrates the composition elements of windfield-source-basin system sedimentary dynamics, and their influences on the sedimentary processes as well as the research methods. Under the guidance of this theory, authors take the modern depositional systems from Qinghai Lake and the ancient depositional systems from

Paleogene Bohai Bay Basin as cases study and establish modern and ancient models for windfield-source-basin system sedimentary dynamics.

The introduced new concept "windfield" by Prof. Zaixing Jiang promotes the study of sedimentology from traditionally "unitary facies mode" and "binary source-to-sink mode" into a new view of "ternary sedimentary dynamics mode", involving wind, source, and basin elements. This improves the explanation on mechanism of depositional systems (including clastic and carbonate rocks) and the prediction on the distribution of unknown depositional systems (and reservoir). The research ideas windfield-source-basin system sedimentary dynamics not only improves the development of sedimentary facies, depositional system and source-to-sink system theory, but also enriches and expands the lacustrine sedimentology theory and fill the blank in this field. It is of great significance in sedimentology and paleo-climate study, and will provide a new theory and method for further exploration of sand body in mature petroliferous basin.

September 2016

Chengzao Jia
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Petro-China Company

Foreword III

Since Charles Lyell inherited and developed "uniformitarianism" after James Hutton, the creed "the present is the key to the past" has influenced the geological science up to now, and also become the core basis of sedimentology. It is not difficult to find out that reports of flume experiments and modern sedimentary simulation is continuing without an end and a large volume of papers have been published on authoritative journal of sedimentology and petroleum geology. By observing the complex depositional processes, these two types of work complete the study of sedimentary dynamics and facies models and exert a far-reaching influence in the academic research. However, "the present is the key to the past" does not apply to every situation due to the lack of geological records and information of some ancient events in the modern deposits such as the Paleocene/Eocene boundary event, Cretaceous oceanic anoxic events and oceanic red beds and other major sedimentary geological. The objective existence of these strata provides a basis for continuously mining the boundary conditions that controls the complicated depositional processes. Hence, "the present is the key to the past" cannot express the ancient geological process completely, and "the combination of ancient and modern" is equally important as well.

Sedimentology was introduced from the west, whereby some concepts or theories, such as facies, facies model, sequence stratigraphy, sedimentary system and source to sink system, were of milestone meanings. They were developed by the western sedimentologists, and our domestic sedimentologists mostly just follow their work and use them as reference without breakthrough. Notably, this book, by taking China's continental basins as the research objective and modern deposition from Qinghai Lake and ancient deposition from the Paleogene Bohai Bay Basin as case studies, combining ancient and modern, emphasizing wind as a control factor for depositional system as well as its interaction with the source and basin dynamic, on the basis of the traditional model and depositional system, proposes the "trinary system of windfield-source-basin system sedimentary dynamics", which is applicable in lacustrine and marine sediments. The theory of this system is originated from China's continental lake system and breaks the shackles of local facies model, depositional system and source to sink system, which is a promotion and innovation of China's continental lake sedimentology. In addition, the paleowindfield is indispensable in paleoclimate study, but it is still weak. The framework of the windfield-source-basin system makes the reconstruction of paleowindfield possible. Using the theory of windfield-source-basin system sedimentary dynamics in petroliferous basin provides a new way to predict oil and gas reservoir.

The windfield- source-basin sedimentary dynamics is the crystallization of Prof. Zaixing Jiang and his team's many years' work. It sets a good example of sedimentology study for adhering to the methodology of "vertically step-down and laterally interactive cross disciplines", which is representative and of potential replication. At the occasion of the book being published, I would extend congrats via this foreword!

October 2016

Chengshan Wang
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Preface

Sedimentary processes take place in preferable depositional environments or sedimentary basins and consequently result in the formation of sediments and sedimentary rocks. The formation and distribution of these sediments and sedimentary rocks is controlled by provenances, paleoclimate, and the sedimentary basins.

The concepts of lithofacies, sedimentary facies, facies model, and depositional system have been proposed to understand the distribution and genesis of depositional systems, and eliminate the prediction uncertainty on sand bodies.

The source-to-sink system theory combines sedimentary bodies in the basin with their sediment sources and transportation path in order to better understand the processes of how sedimentary bodies formed. It is well known that climate plays an important role in controlling the sedimentary processes, and there have been a large volume of literature published regarding the influence of temperature and humidity on the weathering of source rock and its production, and physical, chemical and even biological conditions in the basin, and their further influence on the sedimentary characteristics. However, with respect to the important component of climate, the research on how the windfield (including wind direction and wind power), influence the sedimentary processes is still not well-understood. Although the eaolian research has become increasingly mature, the influence of wind on aqueous depositional environment and its sedimentary response is still the weak section in depositional process study. The first reason is that it relates to the cross field of Meteorology and Sedimentology; second, windfield is difficult to be recorded and to be identified in ancient strata resulting in the recovery difficulties in ancient windfield. A series of studies suggest that it is easier to form waves in windward area of shore and shallow sea (or lake) due to the wind blowing in the oceans and lakes. And these waves, affected by the topography during their propagation, are main factors controlling the formation of series of sand bars parallel or oblique to the shoreline. The geometry and size of these sand bars are related to waves and wind power. Therefore, through the identification and measurement of sand bars, paleo-wind direction and paleo-wind power can be quantitatively recovered, which further provides methods for paleowindfield reconstruction. In a sedimentary basin, though both controlled by the internal basin parameters and source condition, sediments distributed in the windward area significantly differs from those of leeward area. Most onshore and shallow water depositional systems themselves are influenced by the wave action, suggesting that the windfield is an important parameter controlling the deposition. These three factors work together and exert full control of the genesis and distribution of depositional systems. The above illustration shows how the windfield-source-basin system sedimentary dynamics is put forward. The core of the theory is to introduce windfield into sedimentation, and emphasizes its interaction with the source and basin dynamic. The "Trinary dimensional attribute" of windfield-source-basin system sedimentary dynamics is improved from traditional "single dimensional attribute" of sedimentary facies and sedimentary model and "binary dimensional attribute" of source to sink system. This makes the genetic explanation on depositional systems (including clastic and carbonate) more reasonable and the prediction of depositional system (or oil reservoir) in unknown areas more comprehensively and accurately. In addition, quantitative recovery method proposed in this book fills up the blank in the area of quantitative recovery in the atmospheric circulation in deep time. Furthermore, the source, reservoir and cap rocks in the petroliferous basin are also constrained by the windfield-source-basin system sedimentary dynamics, which provides a new view for petroleum geological evaluation.

This book consists of seven chapters. Chapter 1, written by Zaixing Jiang, Junhui Wang and Qing Li, points out the changing of the attention of the sedimentological community in the recent 100 years and the focus of sedimentology gradually shifted from the initial establishment of scientific facies models and explaining depositional environment to explain factors controlling the depositional processes. These control factors include climate, tectonic, source etc, whereby the windfield is considered as an important climate parameters and should be paid more attention as it widely influences the depositional system. Therefore, the genesis and distribution of depositional systems can be summarized as a combined effect of wind, source and basin and the windfield-source-basin system sedimentary dynamics is based on the combination of these factors. Chapter 2 (written by Zaixing Jiang and Junhui Wang) elaborates each element (wind direction, wind power, provenance, topography, water depth etc.) of windfield-source-basin sedimentary dynamic and their effects on the depositional processes. The interaction between various elements and their corresponded deposition are also analyzed. This chapter summarizes and puts forward the recovery method of various elements; improves the trinary sedimentary dynamics system comprehensively considering windfield, source and basin; and sets a classification scheme of depositional systems based on the windfield-source-basin system depositional dynamics. In Chap. 3 (written by Ji Chen and Zaixing Jiang), a modern example of windfield-source-basin system sedimentary dynamics is studied and the related depositional model is established, whereby the modern example is from the Qinghai Lake, by comparison of the leeward with abundant sediment supply and the windward system of relatively less sediment inputs. The leeward system in proximity to source area, consists of alluvial fan, fan delta, rivers and delta. The windward system with weak provenance includes eolian dune, beach barrier, lagoon, littoral and beak-shaped estuary. These modern deposits provide examples for understanding the concept of windfield-source-basin system sedimentary dynamics. Chapter 4 (written by Junhui Wang, Zaixing Jiang and Yuanfu Zhang), conducts the sequence stratigraphy and depositional system study on the fourth Member of Shahejie formation of the Paleogene in Dongying Sag. Based on the core, well log and seismic data, the research ideas and methods apply windfield-source-basin system sedimentary dynamics to recover the paleo-waterdepth, paleogeomorphology, paleoprovenance and paleowindfield. A comprehensive research on the depositional system, their genesis and controlling factors and the model of windfield-source-basin system sedimentary dynamics are presented in this chapter. The middle Eocene evidence of ancient East Asia monsoon is found and its control on sedimentary system is discussed as well for the first time. Chapter 5 (written by Xiabin Wang, Yuanfu Zhang and Zaixing Jiang) illustrates the sedimentary characteristics, genesis types and control factors in the fourth Member of Shahejie Formation of the Paleogene in Liaohe Basin. The beach bar in west Liaohe depression sand body was mainly developed in the early lowstand systems tract and transgressive systems tract. According to the sedimentary genesis, including depositional processes and sediment source, the beach bar can be subdivided into five categories: delta laterally modified, delta front modified, bedrock modified, delta submerg modified and storm modified. The distribution of beach-bar sand body is mainly controlled by the trinary system: wind, source and basin. Chapters 6 and 7 give examples of coarse clastic rocks formed under the background basin of weak wind but large sediment supply. Chapter 6 (written by Hui Liu and Zaixing Jiang) focuses on Daxing conglomerate from Paleogene in Langgu Sag. By detailed core observation and description, reconstruction of palaeoprovenance and paleotopography, three genetic models of the Daxing conglomerate are established, namely fault-trough gravity flow, nearshore subaqueous fan of debris flow and nearshore subaqueous fan of mudslide. The reservoir quality is related to such genesis models. Chapter 7 (written by Lijing Zheng and Zaixing Jiang) elaborates the research on sedimentary characteristics of dense carbonate breccia deposits, tectonic activity, provenance and basin of the third Member of Shahejie Formation in the Paleogene in Shulu Sag. The conglomerate is divided into two categories: the fan delta conglomerates formed by the interaction of alluvial fan and lakes, and slump fan conglomerates and seismites triggered by earthquake. The reservoir quality of the conglomerate beds with different genesis and different oil-bearing property are discussed in this chapter. The whole manuscript is chiefly edited by Finally Zaixing Jiang.

This book embodies the author and his team's researches and achievements of more than 10 years. They are funded by the following: the National Science and Technology Major Projects "Large Oil and Gas Fields and Coal-bed Methane Development"; "11th Five-Year" the China National Key Research Project (Oil and Gas Exploration on New Reservoir Geology and Evaluation of Oil and Gas, 2009ZX05009G002); "12th Five-Year" the China National Key Research Project (Oil and Gas Exploration on New Reservoir Geology and Evaluation 2011ZX05009G002); "13th Five-Year" the China National Key Research Project (Genesis of Terrestrial Deep-Water Reservoir and New Methods for Geological Evaluation 2017ZX05009-002), the National Natural Science Foundations (Lake Sedimentary Simulation Based on Beach-bar Deposition 41102089, Lacustrine Beach-bar Sand Geological Quantitative Prediction 41572029, Quantitative characterization of paleowind field based on beach-bar deposits – take the Eocene Dongying Depression, Bohai Bay Basin as an example 41702104); Shengli Oilfield of Sinopec Group Huabei Oilfield of Petro-China Limited Company and Liaohe Oilfield of Petro-China Company, Oil and Gas Sedimentary Geology Innovation Team of Ministry of Education. Significant in-depth guidence was given from academicians Chengzao Jia, Yongsheng Ma, Yuzhu Kang, Deli Gao, Tingdong Li, Chengshan Wang, Shufeng Yang, Suping Peng, Meifeng Cai and Wenzhi Zhao. Important supports, discussions and advices were given by professor-level senior engineers Shanwen Zhang, Guoqi Song, Yongshi Wang and Huimin Liu from the Shengli Oilfield: professor-level senior engineer Xianzheng Zhao from Dagang Oilfield; professor-level senior engineers Yiming Zhang and Ruifeng Zhang from Huabei Oilfield; professor-level senior engineers Weigong Meng, Zhenyan Chen and Junfeng Shan from Liaohe Oilfield; Prof. R. Steel and C. Fulthorpe from the University of Texas at Austin; Prof. E. Gierlowski-Kordesch from Ohio University; Prof. D. Nummedal from Colorado School of Mines; Dr. H. Lu from Shell oil company; Prof. R. Koch from Nuremberg University in Germany; Prof. Hongwen Deng from China University of Geosciences (Beijing), Prof. Longwei Qiu from China University of Petroleum have given many comments for improving the results as peers. Dongmei Luo and Wenmao Xu. Their help is greatly appreciated! A number of doctors and masters involved in the study have made an important contribution to the formation of the results. They are: Weili Yang, Xingpeng Peng, Yaming Liu, Guobin Li, Jijun Tian, Guiju Chen, Shu'an Xiang, Li'an Liu, Guiting Yuan, Ning Zheng, Shenglan Wang, Lanzhi Qin, Wei Zhao, Lei Feng, Weiling Li, Haowei Zhou, Xiaojie Wei, Shuai Yuan, Weiwei Gao, Junjie Li, Xiaowei Sun, Xiangxin Kong, Haipeng Li, Wenmao Xu, Shan Song, Chao Liu etc.

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Beijing, China Zaixing Jiang
May 2016

Contents

1 The Emergence of Windfield-Source-Basin Dynamics

1.1 Depositional System Advances

Sedimentary environment, facies model, depositional system, source-to-sink system and so on have been put forward in the past two centuries, and have become important milestones in the different development stages of sedimentology.

1. Facies. The concept of "facies" was first introduced by the Swiss geologist Gressly into sedimentary rocks research in the late 1930s. He believed that "facies is the sum of sediment changes, the performance of one or other lithological, geological, or paleontological differences." Different sedimentologists have different understandings of this concept. Sedimentary facies in China is defined as "the synthesis of sedimentary environment and sedimentary rocks formed in the environment" (Jiang 2003). By definition, a facies contains both a description attribute (material composition) and an interpretation attribute (depositional environment).

In a geological record, a particular "facies" has similar lithological, physical, and biological features that distinguish it from adjacently overlying, underlying, and lateral "facies" (Fig. 1.1). Because a particular "facies" is formed in a certain environment, we can deduce the sedimentary environment through the analysis of "facies". In fact, after the emergence of the "facies" concept, the purpose of sedimentary facies study focused on the interpretation of the facies parameters or environmental boundary conditions to determine the sedimentary environment. For example, we can determine whether a sedimentary body belongs to a deltaic environment by investigating whether the planar form of a deposition unit is lobate, whether there is a mixture of land and sea organisms, and whether the sedimentary sequence is a coarsening upward sequence. The analysis of the sedimentary facies is controlled by firsthand data, which is usually fragmentary and thus is more frequently used to explain the local sedimentary process and the sedimentary environment. As Fig. 1.1 shows, we can analyze local sedimentary processes and environments of facies A and facies B in an outcrop by studying their lithology, texture, structure, and paleontology, but would be difficult to extend depositional interpretation beyond the outcrop.

2. Sedimentary environment. The sedimentary environment is defined as a surface unit of the Earth's landscape that is physical, chemical, and biologically different from the adjacent area (Selley 1996). The sedimentary environment consists of a series of following environmental conditions, including (1) natural and geographical conditions; (2) climatic conditions; (3) structural conditions; (4) physical conditions of sediment; (5) geochemical conditions of sediment (Jiang 2003, 2010a). The classification of sedimentary environments on Earth's surface is shown in Fig. 1.2.

The sedimentary environment is a place where sedimentation occurs, and the decisive factor for the formation of sedimentary rock. The concept of facies has the interpretation ability to define the sedimentary environment. For example, the deltaic facies are the physical records of the interactions between rivers and marines (or lake) in a land-sea (or lake) transitional sedimentary environment. The ultimate goal of the facies interpretation is to reconstruct the paleo-sedimentary environment (He et al. 1988). However, this process is difficult in practice because, as noted above, there is little or no necessary and sufficient condition to define a sedimentary environment. Some conditions are necessary but not sufficient; Some conditions are sufficient and not necessary (He et al. 1988). Therefore, the sedimentary environment interpretation is a result of a comprehensive interpretation of a variety of boundary conditions, with multiple solutions. In addition, since the recovery of the sedimentary environment is largely dependent on the principle of facies analysis, the sedimentary environment interpretation is also a local scale study, which is highly dependent on the firsthand data.

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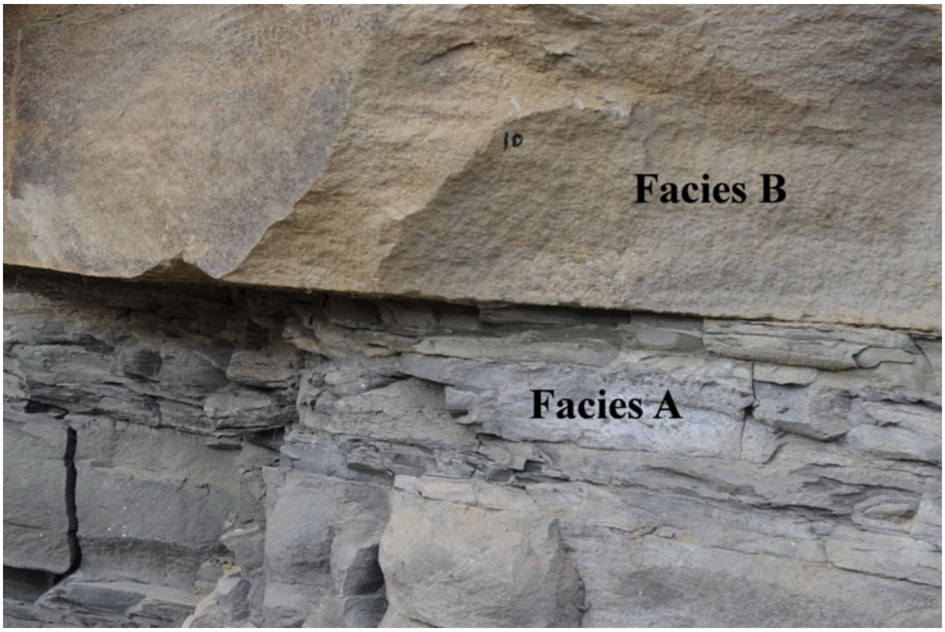

Fig. 1.1 Two different lithofacies (Triassic Sanshuihe outcrop in Xunyi county, Xianyang city)

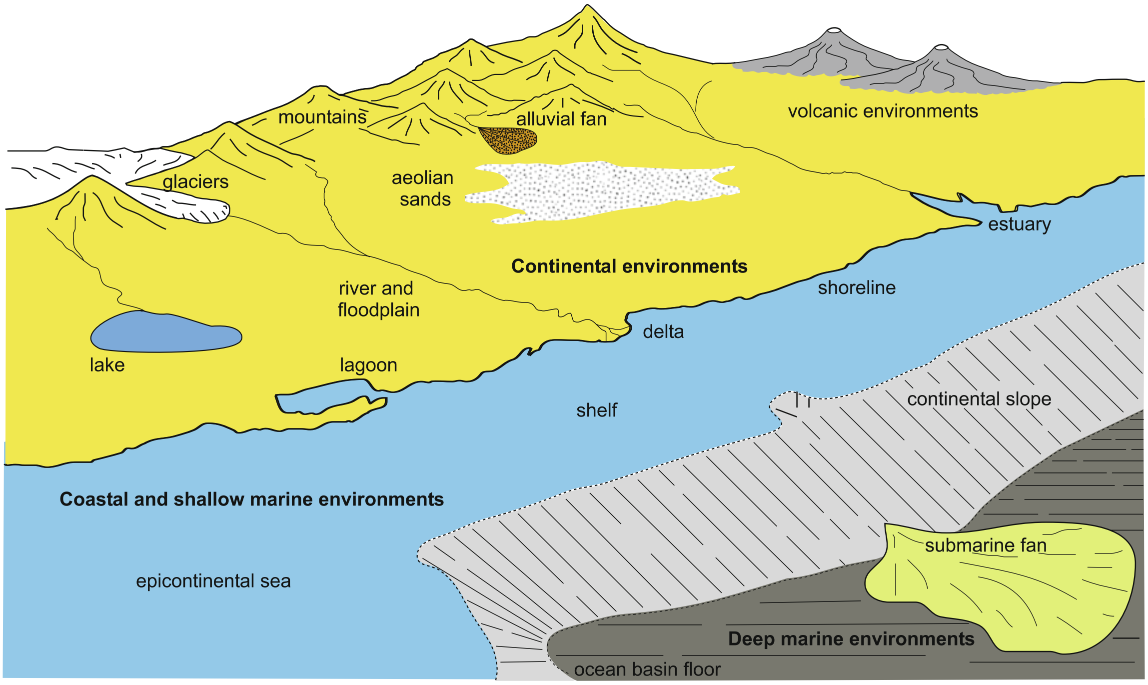

Fig. 1.2 Summary diagram of principle sedimentary environments (from Nichols, 2009)

3. Facies model. The concept of facies model was proposed by the famous sedimentologist Roger Walker in 1970s. Since "Facies Models" (Walker 1979) was published in 1979, it has been regarded as a monument in the modern history of sedimentology. The facies model is an ideal and general sedimentary facies expressed in terms of diagrammatic, literal, or mathematical methods, and can help to understand complex hydrodynamic mechanisms and sedimentary processes. The facies model is built on a variety of physical records (including sedimentary texture, structures, etc.) that is produced by the variation of the hydrodynamic regime during deposition, and highly summaries the sedimentary environment, sedimentary processes and its products (Walker 1979). The sedimentary environment, with different deposition processes and hydrodynamic mechanisms, forms different physical records and therefore has different facies patterns.

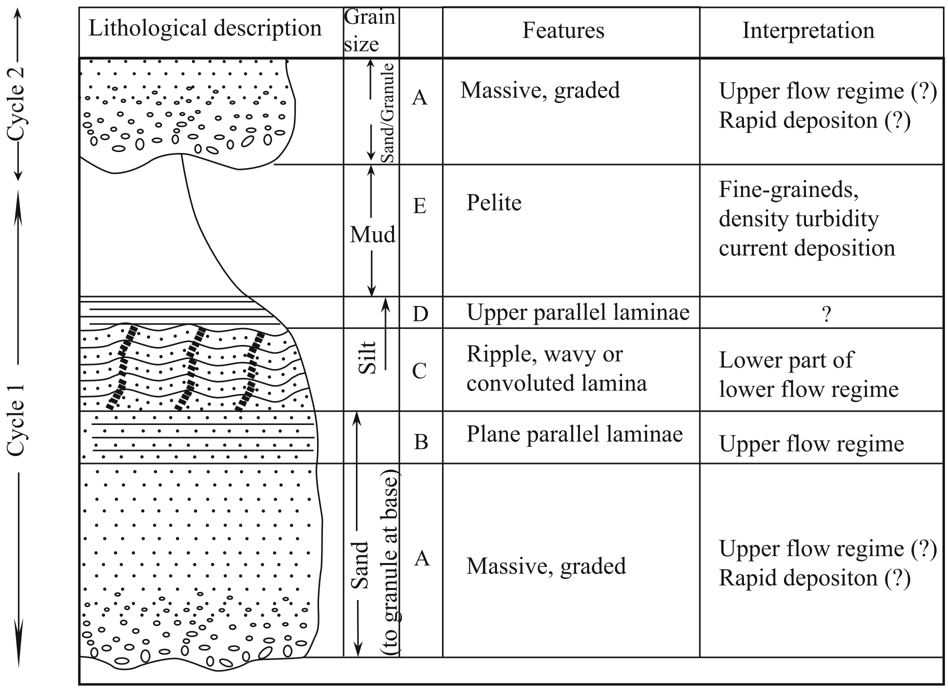

Fig. 1.3 Bouma sequence and interpretation (modified from Bouma 1962; Feng 1993)

Sedimentologists have established a variety of standards or general models of sedimentary facies for the interpretation of sedimentary environments through the observation of geological records, the study of modern sedimentary processes and experimental simulations. For example, the famous Bouma sequence describes the hydrodynamic state for turbidite deposition (Fig. 1.3). The facies model, from the perspective of hydrodynamic interpretation, provides a template and reference for the interpretation of sedimentary facies. Therefore, it can be concluded that the study of facies models is still within the scope of facies and sedimentary environments analysis, and is a local scale study.

4. Depositional system. This concept was first applied by the Texas Bureau of Economic Geology in the late 1960s to the Gulf of Mexico, and was then referred to an assemblage of genetically related sedimentary facies, or an assemblage of three-dimensional lithofacies that is produced by sedimentary process (Davis 1983; Posamentier et al. 1988). The depositional system concept is widely used since it was proposed. Therefore, the genetically related sedimentary facies is the basic unit of the depositional system. Since the concept of “facies” has been used extensively, Galloway (1986) suggested the use of “genetic facies” to represent the basic building blocks of the sedimentary system (Li et al. 2004), which means a particular depositional system is built on specific “genetic facies”. Within the depositional system, the different genetic facies are spatially interconnected and regularly arranged (Fig. 1.4). The different genetic facies within the same depositional system are not isolated but are causally linked to each other by one or several sedimentary processes. In addition, the depositional system incorporates the concept of time, emphasizing the evolution of sedimentary facies assemblages associated with depositional processes and genesis. The physical behavior of a depositional system is a three-dimensional depositional geological body defined by unconformity or depositional hiatus.

The compressive study of the depositional system is a summary process of sedimentary facies distribution, which is also the basis of basin analysis and paleogeographic reconstruction. Therefore, the concept of the depositional system is proposed to further extend the research scale of sedimentology, which previously based on the establishment of local facies model and the interpretation of sedimentary environment (He 2003), and is the continuation and development of sedimentary facies research (Wang and Li 2003). The depositional system analysis method is to study sedimentary process from a higher angle, pointing out the genetic facies exists as a system. Therefore, the study of the sedimentary system is focused on the evolutional process of sedimentary facies assemblage, which is related to sedimentary processes and genesis. Depositional system has gradually become the basic unit of deposition process research.

5. Source-to-sink system. The denuded landforms of the orogenic or uplift areas and the depositional landforms of

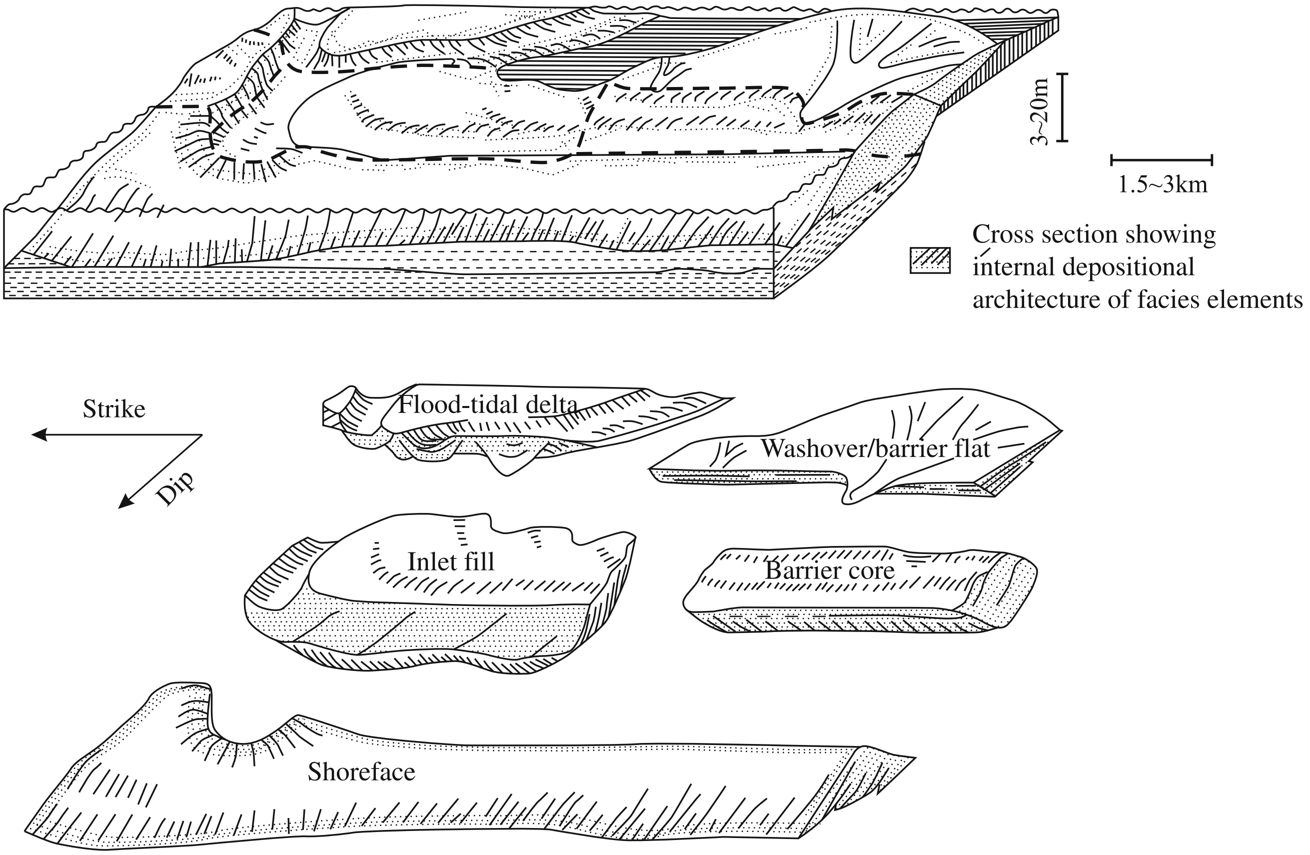

Fig. 1.4 "Genetic facies" of barrier island in barrier shore system (modified from Galloway 1986)

the basin area are two basic landform units on the Earth's surface (Lin et al. 2015) and are linked by the sedimentary transportation system. The process of sediment eroded from the source area, including physical and chemical weathering, transportation and deposited in the sedimentary basin constitutes the source-to-sink (S2S) system. Source-to-sink system recently is a hot research topic in the field of international geosciences. Sedimentary source-to-sink involves sediment erosion, transportation, and deposition. The source-to-sink system is to study the autogenic, allogenic processes and feedback mechanisms that control sediment delivery from source to sink (Sømme et al. 2009).

In the 1990s, the MARGINS Program, led by the US National Science Foundation (NSF), has extensively studied the source-to-sink system and made significant achievements in the past decades. The core scientific goal of the project is to comprehensively study the dispersion of sediments on terrestrial and in marine environment within a time scale of various depositional processes and to synthesize the elements of the system through observation, experiment, and theory. The key question is focused on how tectonism, climate change, and sea level changes affect the generation, transport, and accumulation of sediments (including particle and dissolved matter), revealing the processes of erosion and sediment transportation on the Earth's surface, and how the stratigraphic records produced by the interaction of deposition processes. The concept of the source-to-sink system initially emphasizes the quantification of surface processes and combines sediment fluxes with geological processes. At present, the research of source-to-sink system is an important subject in the field of earth sciences.

The geologic information preserved in the source-to-sink system is a record of the whole Earth's surface dynamics from the erosional zone to the deposition area. It is necessary to study the sediment erosion in the source area, transportation in the transfer zone and deposition in the basinal sink as a whole genetically linked system. For example, the current study of the source-to-sink system from land to sea is to reveal how sediments are eroded from uplift region, transported to the continental shelf area, and finally deposited in deep-sea area (e.g., Sømme et al. 2009, 2013; Sømme and Jackson 2013). This source-to-sink system consists of several depositional systems (Fig. 1.5) from the catchment (erosional area), alluvial-coastal plain, shallow continental shelf, continental slope, and deep-sea basins. In this process of surface dynamics, it will be influenced by external forces such as tectonism, climate change, and sea-level rise and fall. Therefore, such research involves a wide range of

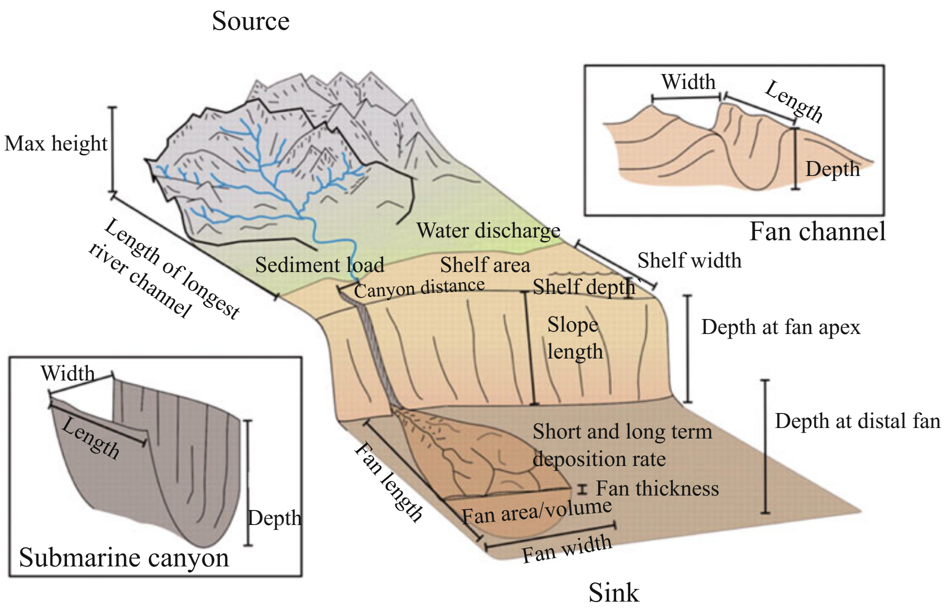

Fig. 1.5 Geomorphology and sedimentological features in the source-to-sink system (Sømme et al. 2009)

interactions and intersections between solid earth geology, geomorphology, atmospheric science, environmental science, and oceanography, and focuses on the role of external influences on erosion processes and sediment transportation processes (Lin et al. 2015). The proposed source-to-sink concept advances the sedimentary research into a more integrated science and expands the research scope beyond the depositional system. However, the source-to-sink system is still focused on the study of sedimentary characteristics and deposition process interpretation (from the source to sink in the longitudinal direction). The interpretation of the sedimentary system distribution in the region (lateral) is still not fully explored.

1.2 The Influence of Windfield on Depositional System

Sedimentary facies research focused on the description of local facies type, mostly for the purpose of depositional environments interpretation, while facies model emphasizes hydrodynamic changes in vertical, is an important supplement of sedimentary facies research. Depositional systems regard the different facies are genetically related and should be treated as a whole system, driving the sedimentary research from basic facies unit to completely depositional system. The source-sink system analyze the whole process of sediment delivery from the source area to basinal sink and reveal how the tectonism, climate change, and sea level rise and fall affect the sediment erosion, transportation, and deposition. It emphasizes the genetic link among depositional systems in one dimension along the depositional pathway. The research scopes mentioned above have gradually changed from simple to complex, from partial to whole, from the study of the sediment itself to the controlling factors of sediment erosion, transportation, and deposition.

External controlling factors for depositional system include climate, tectonism, sediment source, sea level rise and fall and so on. The fully understanding of these external factors is the key to study the distribution of depositional system and matching relationship between different depositional systems. Among these external controlling factors, the influence of paleoclimate on sediment deposition is less explored so far, especially the influence of the windfield is often neglected. The windfield is an important geological force, not only has affected the sediment erosion, transportation, and deposition, it can also generate waves by blowing water body in the basin to form a broad coastal zone and control of the coastal and shallow water deposition. The effect of the windfield on the sedimentary system is common and usually expressed in the following ways.

1.2.1 Influence of Windfield on Clastic Depositional System

1.2.1.1 Wind and Eolian Depositional Systems

The most direct effect of the windfield on the clastic deposition system is the formation of an eolian depositional system or desert system. Because the physical weathering is dominant in arid climate region, the products of weathering are usually rich in sandstone. At the same time, due to limited rainfall, large evaporation, lack of vegetation, long-lasting drought status of earth surface, the wind has a strong influence on earth landforms. The effect of windfield on earth surface can be expressed in three ways, including erosion, transportation, and deposition. The formation of the alveolar stone, wind-eroded niche, eolian mushroom, wind erosion column, wind erosion depression, wind erosion valley, rock desert, and Gobi desert on earth surface are the result of wind erosion.

Although the transportation capacity of the wind is much smaller than the water, it still can carry a huge amount of sediment. A storm can carry hundreds of thousands of tons to hundreds of millions of tons of material (Chen 2006). As the wind blows a long distance or the wind encounters a variety of obstacles such as mountains and trees, the energy of wind waves and the sediment carried by the wind begin to be deposited. The sandy sediments carried by traction or saltation can result in sand dunes and even deserts, whereas silt and dust transported in suspended form will form eolian loess deposits.

1.2.1.2 Influence of Windfield on the Lacustrine System

Wind does not only directly act on the sediment, it can also drive other media to move and affect the distribution of the depositional system. In the lacustrine system, lake waves and lake currents are the most obvious hydrodynamic forces driven by the wind.

There are several important physical interfaces in the lake: the flood surface, the dry (low) surface, the normal wave base, and the storm wave base (Fig. 1.6). Among them, the coastal zone above the normal wave base is the area where the lake waves are significant. The lake waves erode, transport, re-deposit previous lake sediments, and produce various erosional and sedimentary landform, such as beach bar. During periods of storm activity, storm deposits are developed between the storm wave base and normal wave base (Fig. 1.6). These deposits are products of

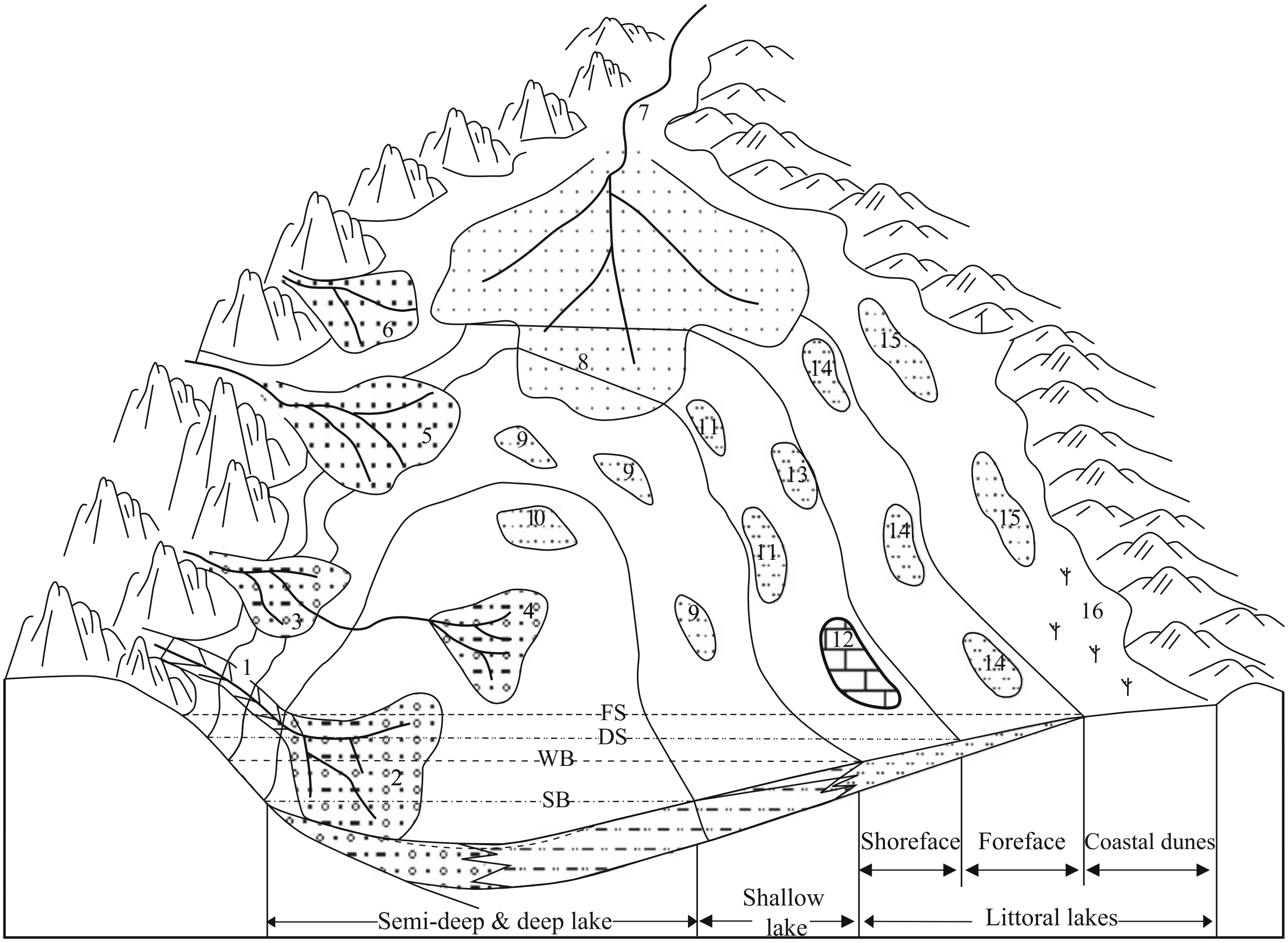

Fig. 1.6 Schematic diagram showing depositional facies in lacustrine basin (from Jiang 2010a). 1—lake margin canyon; 2—subaqueous fan; 3—fan delta; 4—basin floor fan; 5—braided river delta; 6—alluvial fan; 7—meandering river; 8—meandering river delta; 9—tempestite; 10—turbidite; 11—outer bar; 12—carbonate beach bar; 13—inner bar; 14—coastal bar; 15—aeolian sand dunes; 16—swamp; FS—flood surface; DS—dry water surface; WB—normal wave base surface; SB—storm wave base

windfields that reshape the depositional system in a lacustrine basin. In addition, the delta system developed in the shallow water area, the redistribution of sediments can also occur under the action of wind and waves. For example, the sheet sands and sand beach mouths in the delta front are the results of the redistribution of delta sediment by lake waves and currents. If the waves are strong enough to outweigh the role of the river, the river mouth weill even migrate. In the whole lacustrine depositional system, most of the sediment deposited above normal wave base are more or less affected by wind and waves, excepted the subaqueous fan that deposited below the wave base are nearly unaffected by waves.

In addition to the role of the waves, the friction of wind on the lake surface and the pressure of wind on the wave of the windward surface will make the surface water move forward and generate wind-driven flow. Wind-driven flow is common in a large lake and can cause a large-scale and extensive flow of water in the lake. The latest research indicates that wind-driven flows can be either surface currents or bottom currents, which can act on sediments and modify the lacustrine sedimentary system (Fig. 1.7; Nutz et al. 2015). The circulation of surface currents generally follows the wind direction and rework the sediments near the shoreline, resulting in sand bar and barrier bar deposits. Surface currents will eventually converge in the windward shoreline and generate bottom currents and compensated by the bottom currents. The bottom currents are, in general, opposite to the wind direction and form a “wind-driven water bodies” (Nutz et al. 2015). The compensated bottom currents generally occur beneath the wave base and carry sediments into the deep water during storm period, forming subaqueous prograding wedges and sediment drifts. The lake dominated by the wind-induced water circulation can be called wind-driven water bodies (Nutz et al. 2015). In fact, the flow dynamics of the wind-driven water circulation could be more complex (Han et al. 2015).

1.2.1.3 Influence of the Windfiled on the Land-Sea Transitional Depositional System

There are 80% of the world’s coast and shelf areas subject to rework of waves, which are also largely affected by the winds. The land-sea transitional system is one of the depositional systems under an obvious wind-wave influence. The land-sea transitional depositional system includes delta, estuary bay and shore system. These three systems are to some extent unified and interconnected (Fig. 1.8). During the period of sea level regression, the sediment supply is more dominant and it is easy to form a river-dominate delta. Meanwhile, the deltaic system can be divided into river-dominated delta, tide-dominated delta, and wave-dominated delta, according to the relative strength of tide, wave, and river.

One of the major influences of the windfield on the land-sea transitional system is to rework delta system by waves. Because the sediment input from the river will be redistributed under the action of waves, a series of beach

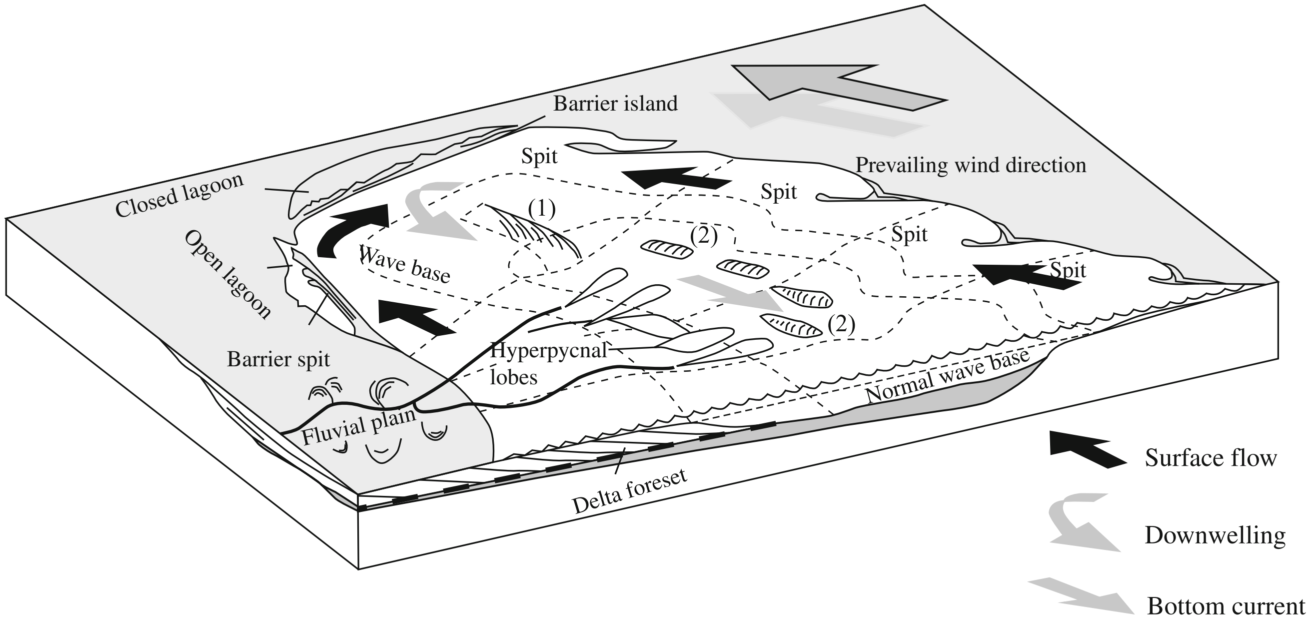

Fig. 1.7 Sedimentary model under control of wind driven water bodies. The sediment in the vicinity of the shoreline is reworked by wind driven water bodies to form spit and barrier island. Along the wind blowing direction, compensation base flow (downwelling) is formed near shoreline and backflow (bottom current) is formed above normal wave base, resulting in the development of subaqueous prograding wedge and sediment drift (modified from Nutz et al. 2015)

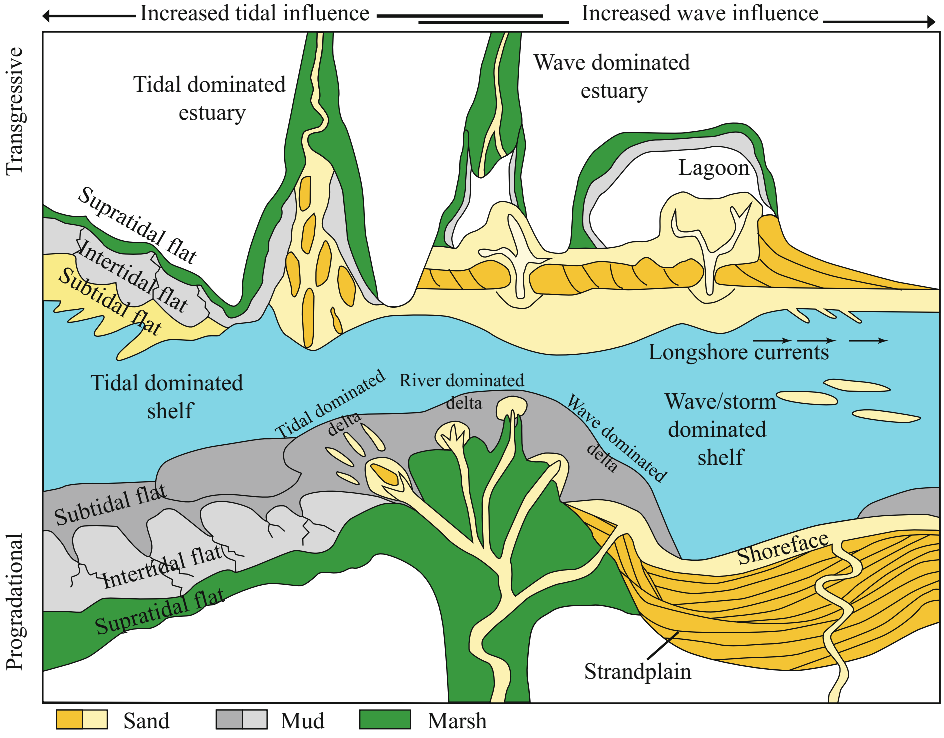

Fig. 1.8 Classification of coastal-shallow marine environments (modified from James and Dalrymple 2010) based on the relative strength of tide, wave and river, as well as sea level rise and fall. The upper part is the classification of coastal-shallow marine environments during transgression, while the lower part is the classification of coastal-shallow marine environments during progradation

ridge sands that are parallel to the coast will be formed on both sides of the river mouth. Only in the area adjacent to the river mouth, large volumes of sands will be deposited and formed bow-shaped or beaklike delta. The Brazilian San Francisco River Delta or the Rhone Delta is a typical example. If the wave force is strong enough to completely overcome the force of the river, together with a strong one-way longshore flow, it will shift the river mouth to be parallel to the shoreline and significantly redistribute the sands, resulting in barrier island and beaklike delta. African Senegal River Delta is a typical example.

The second effect of the windfield on the land-sea transitional system is to form barrier-free shoreline depositional system. At the same time, the erosion, transportation, and deposition of the sediments are fully controlled by the wave. According to the wave hydrodynamic mechanism, the sedimentary environment can be further divided into nearshore, foreshore, and backshore.

The third effect of the windfield on the land-sea transitional system is reflected by the impact on the estuarine system, making the estuary bay closed. In the process of transgression, the sediment supply is reduced and the tides or waves from sea become more dominant, favoring an estuarine bay system. According to the relative strength of tidal and wave, the estuarine bay system can be further divided into tide-dominated and wave-dominated systems. In the tide-dominated estuarine environment, the flood tide and ebb tides form a scouring ditch and a long and narrow linear tidal sand ridge following flow direction in the estuarine bay. However, with the enhancement of wave action, the reciprocal motion of the waves and the associated longshore currents dramatically redistribute the tidal sand ridge. The trend of the sand body gradually becomes parallel to the coastline, finally forming barrier island-lagoon-estuarine sedimentary environment.

1.2.1.4 Influence of the Windfield on Siliciclastic Shelf Depositional System

The influence of the windfield on the depositional system is also reflected in the siliciclastic shelf depositional system (Fig. 1.9). Seasonal typhoons or hurricanes cause storm waves to penetrate far deeper than normal waves, typically over 40 m and up to 200 m. When the violent storm wave spreads toward the shoreline, the huge energy can form the rising water once the wave encounters coastal area, resulting in storm surge to strongly erode coastal area.

When the wind energy wanes, the storm recirculation (eddy tidal current) carries a large amount of detritus from the eroded nearshore area to the offshore area, forming a density flow to the sea. This kind of fluid has a high flow velocity and can carry detritus up to tens of kilometers or even hundreds of kilometers on the continental shelf. It can significantly erode and modify the sea floor morphology. As the storm energy decays, the flow velocity becomes lower and the clastic material in the density flow becomes to be redeposited to form the shallow marine storm deposition.

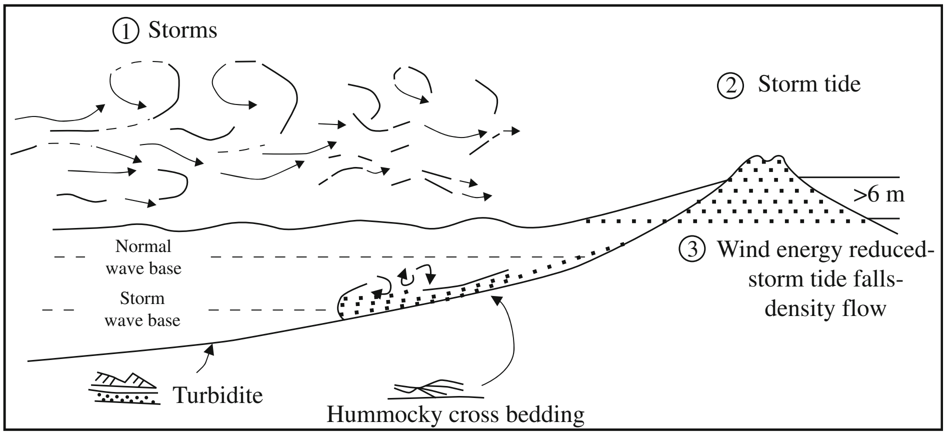

Fig. 1.9 Ideal mechanism of how the storm deposits formed (from Feng 1993)

1.2.1.5 Influence of the Wind (Wave) on Siliciclastic Depositional System—A Case Study of Beach Bar

The beach bar is a common sand body in the shallow lake (sea) area. It is the general term of beach and bar. Its formation process is mainly controlled by the waves and longshore currents (Komar 1998; Jiang 2010a). Both beach and bar are formed in a very similar environment and overlap each other in vertical and lateral, and thereby sometimes it is difficult to differentiate beach from bar. It is, therefore, to us term beach bar or beach bar complex to describe these types of sand bodies (Wu 1986; Zhu et al. 1994; Deng et al. 2011).

However, they are very different in the formation mechanism and depositional characteristics. The bar is built up by large sediment accumulation, while the formation of the beach is not associated with significant sediment accumulation process. In the plane, the bar is usually in a linear shape and is usually surrounded by sheet-shape beach sands.

(1) The formation of "bar"

The transportation direction and trajectory of the sediments in the coastal zone are strictly controlled by hydrodynamic conditions, so the formation of beach bar is the result of the combined effect of hydrodynamic conditions. At present, there are several viewpoints on the mechanism of the formation of the sand bar, including subgravity wave, breaker wave (or self-organization model), surfing wave mechanism, and coastal spiral flow. In addition, the longshore current system will also rework the sand bar.

1. Subgravity wave mechanism

The mechanism regards the sand bars are formed under the influence of subgravity waves, including surf beat, bound long wave, edge wave and so on, which are often characterized by standing waves (e.g., Carter et al. 1973). The sand bar is formed at the node or antinode of the standing wave. If sediments are mainly transported by bedload flow, the sand bars are usually formed at the node of standing wave. On the contrary, the sand bars are formed at the antinode of the standing wave if the sediments are carried as a suspension (Carter et al. 1973; Short 1975). This mechanism well explains the phenomenon of multiple parallel arranged sand bars in the coastal zone and explains the increase in the distance between the bars along with the offshore distance (Carter et al. 1973; Short 1975; Aagaard 1990).

However, the subgravity wave mechanism has some drawbacks. First, the velocity of subgravity wave is much smaller than that of gravitational wave and wave current. In addition, the model requires that the standing wave energy be concentrated in the specific waveband, but the observation of subgravity wave indicate the wave bed is quite broad. Therefore, the subgravity wave may not be the dominant factor for the formation of sand bars. This mechanism has not been well documented in indoor flume experiments (Dally 1987) or modern coastal sedimentary studies (Osborne and Greenwood 1993; Houser and Greenwood 2005), although they have a good explanation of the sand bars formation.

2. Breakpoint or self-organization mechanism

In recent years, the "breakpoint model" or "self-organizational model" that explains the causes of the coastal sand bar has been widely accepted (Dyhr-Nielsen and Sorensen 1970; Coco and Murry 2007). When waves spread toward the coastline and reach the wave base, they begin to touch sea floor and be deformed due to reduced water depth. As the waves continue to spread, when the water depth is reduced to a critical value, the slope value of the wave begins to reach the limit, causing the wave rewind and broken and the formation of breaker waves. On the one hand, the waves transport sediment to the breaker wave zone. On the other hand, the landward broken waves can form the oscillation wave again and generate a circulation on the shore side of the wave. In addition, when waves propagate to shore, a compensation flow (bottom current) can be formed. Consequently, the breaker wave zone is influenced by both the waves from offshore and coastline. The confluence of landward waves, seaward back circulation, and compensated landward bottom currents caused sediments to be deposited in breaker zone and form sand bars and associated trough (Dyhr-Nielsen and Sorensen 1970; Dally and Dean 1984; Dally 1987) (Fig. 1.10). Therefore, this model believes that the breaker waves control of the offshore location, scale, depth range and formation of the sand bar. The formation of the sand bar, in turn, will interact with the waves. As early as 1948, Keulegan's study found that as the breaker wave bars (shore bar) grows and migrates landward, the position of the breaker waves moves accordingly (Keulegan 1948). The generation and migration and breaker wave sand bars are always corresponding to the movement of breaker waves.

The breakpoint model can be simply expressed as follows. As the wave moves landward and begins to disturb the sea or lake floor, the resulted landward breaker waves and seaward circulation start to accumulate sediments to form sand bars in breaker zone. The formed sand bars, in turn, can interact with the dynamics of waves to reach the new balance and reform sand bars and associated troughs (Houser and Greenwood 2005). In a gentle slope coastal environment, when the waves break at sand bar (shore bar), it can be reformed to a new oscillation wave in the deep troughs. Reformed waves may experience a second or even third breaker process, forming an internal local breaker zone (Qian and Wan 1991). As a result, multiple sand bars can be formed nearly parallel to the coastal zone. Although the mechanism of the self-organization model of sand bar is based on the marine environment, this model can also be applied to the lacustrine environment under certain conditions. This has been tested and validated by the flume experiment (Keulegan 1948) and the modern lacustrine sedimentary study (Greenwood et al. 2006).

3. Surfing Mechanism

The final destination of waves after breaker is to become surfing waves, forming a "surfing backwash zone". When wave move toward the shore by inertia, the water carried by wave either is infiltrated into sediment or returns directly back down along the slope to become backwash wave. This process will keep repeating until the water disappears, or collides with next surfing waves. In the surfing-backwash zone, the transport capacity of surfing waves is stronger than that of the backwash (Masselink et al. 2005), and thus the surfing waves effectively transport coarse sediments to the shore. The sediment is brought up to the highest position where surfing occurs and accumulates there, forming a sand bar spread along the shoreline, called the nearshore bar (Fig. 1.11). Sediment composition of nearshore bar includes sediments from both the source area and insitu relict sediments after erosion. The relict sediments indicate the height of sediment that can be reached by surfacing.

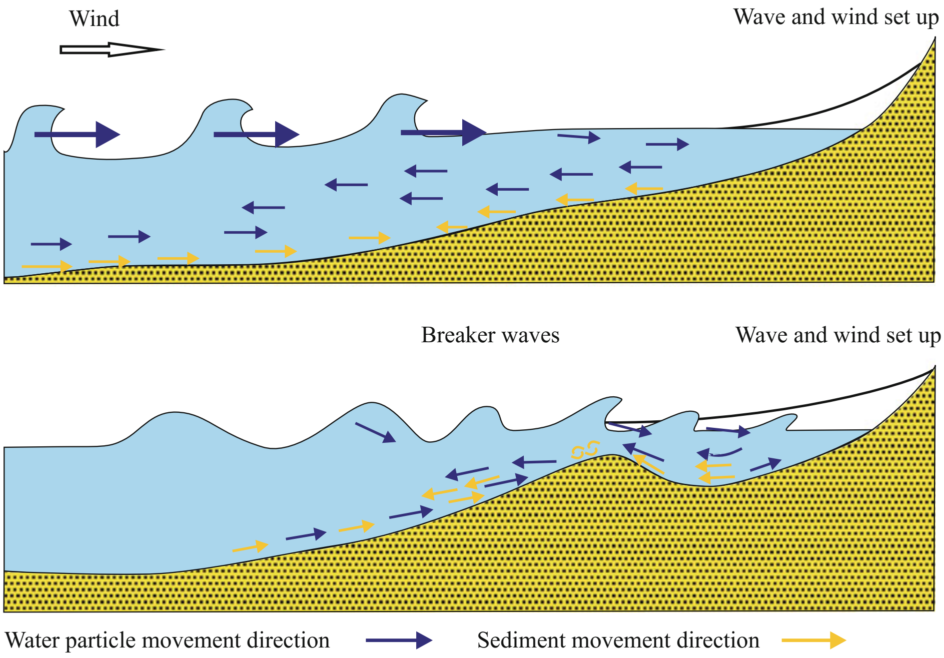

Fig. 1.10 The genetic model of breaker wave bar

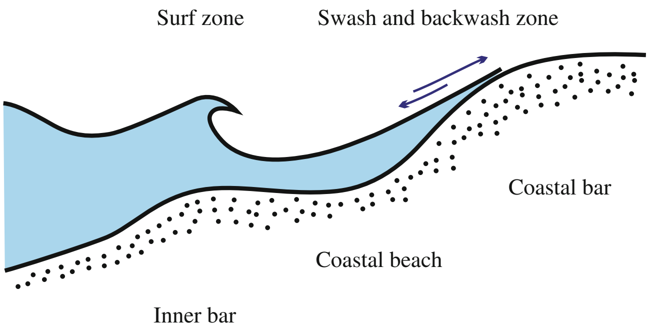

Fig. 1.11 Schematic diagram showing the topography of surf zone and swash-backwash zone

4. Formation mechanism of longshore spiral flow

The spiral flow mechanism of the bar is proposed by Schwartz (2012). Schwartz (2012), by studying Lake Michigan in North America, proposed a longshore spiral flow can be formed when wind-driven waves flow toward coastline in a low skewed angle (Fig. 1.12). According to the different characters of the wave flow, this spiral flow consists of three parts: the oscillation flow generated by the incident wave, wind-driven longshore current, breaker waves driven longshore current. In this kind of sand bar system, the sediments influenced by spiral flow that is parallel to shoreline, can accumulate to form sand bars and evacuate to form inter-bar troughs. In the micro-topography of the sand bar-trough, the trough is mainly controlled by the longshore current, while the sand bar is mainly controlled by the wave oscillation. From midline of trough to bar crest, the strength of longshore current is reduced and the velocity of the water particle track (oscillatory flow) is enhanced. Under such conditions, the sediments are stripped from the troughs and transport to both sides of slopes and form sand bars. Therefore, the erosion mainly takes place in the troughs, result in concentration of coarse-grained sediment and lag deposits. The bar is composed of fine-grained sediment after wave sorting. This process leads to the formation of erosion-dominated troughs and deposition-dominated sand bars. In this mechanism, the amount of net sediment transport is toward the coastal direction. Although the bar crest is influenced by the oscillatory flow, it is also affected by the longshore current. This mechanism has been verified in modern shoreline sedimentation (Greenwood and Sherman 1984; Greenwood and Osborne 1991; Schwartz 2012), but the application of this mechanism to ancient sand bars has not been reported.

5. The rework effect of longshore current

The flow generated by nearshore waves is very complex in the plane. In addition to the reciprocating motion directly generated by the waves, there are two additional kinds of wave-generated flow system. They are: (a) a circulation system composed of a fraction and its associated longshore currents, and (b) a longshore current due to oblique incident waves (Komar 1998) (Fig. 1.13a, b). The two systems are

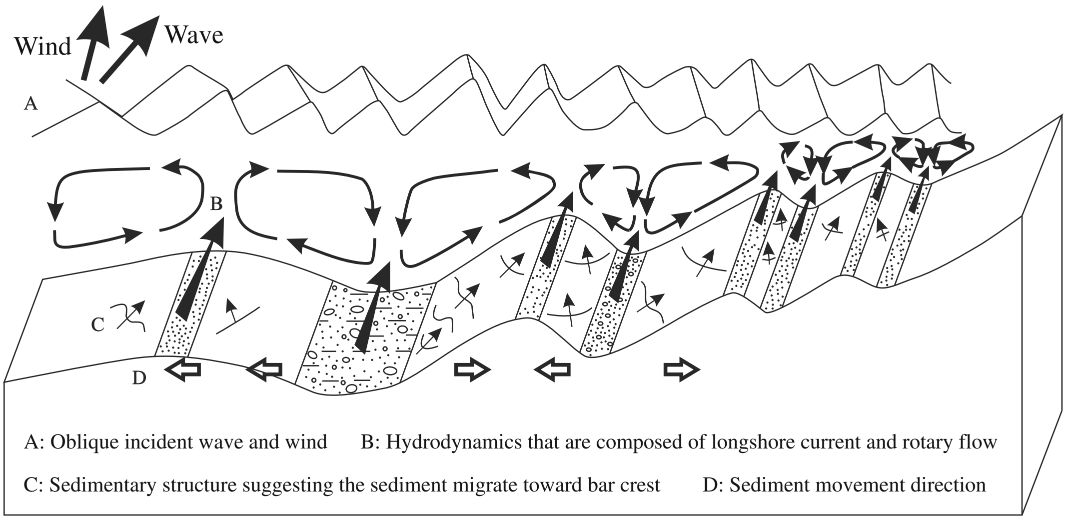

Fig. 1.12 Schematic diagram showing the sand bars in the coastal area that formed by the mechanism of helical flow (modified from Schwartz 2012)

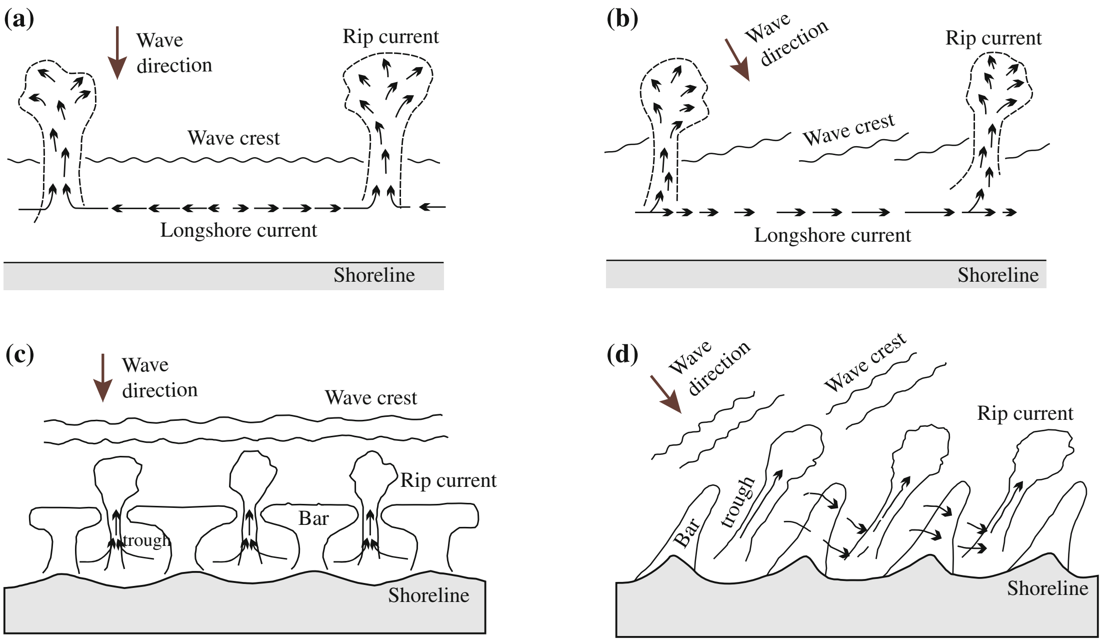

Fig. 1.13 Nearshore circulation system and oblique wave and its modification to the sand bars (modified from Komar and Inman 1970; Komar 1998). **a** The near shore circulation system caused by forward wave; **b** The nearshore circulation system caused by oblique waves; **c** The reworking of sand bars by the near shore circulation system that is caused by forward wave; **d** The reworking of sand bars by the near shore circulation system that is caused by oblique wave

usually coexistent, and the corresponding erosion, transport, and sedimentation play a significant role in the redistribution of sediments.

After wave broken, due to the complexity of the coastal zone terrain, and inconsistent water level that generated by the different wave height along the coastline will generate wave energy gradient along the coastline, which drives the longshore current to move parallel to the shoreline. The flow will converge to the offshore direction at weaker locations, creating a friction stream that can pass through the breaker zone and dispersed in fan-shaped (Komar 1998) (Fig. 1.13 a). The amount of water lost to the offshore direction is compensated by the mass transport of the water from the breaker zone. The seaward moved flow, compensated longshore flow, and friction flow together constitute the circulation system of the coastal zone (Shepard and Inman 1951). The friction flow and associated longshore currents can redistribute sediment and form multiple sets sand bars that are separated by troughs and corresponding shoreline (Bowen and Inman 1969; Komar 1971) (Fig. 1.13c).

When the incident wave skews shoreline, it will also generate a longshore current nearly parallel to the shoreline, flowing along the bar-trough flow system. The longshore current also has significantly affected the transportation of sands and muds in the coastal area (Fig. 1.13b). When the oblique wave reaches the coastal zone, fractured flow and associated channels and bars would be affected (Fig. 1.13b) and adjusted in the direction that parallel to incident wave peak, resulting longshore migration and oblique sand (Fig. 1.13d).

(2) The formation of beach

In contrast to “bar” that is the result of sediment accumulation, “beach” is formed generally with no significant deposits gathering. The beach is mainly sheet-like sand bodies that surround bars, found either between the gaps or outside of bars (Jiang et al. 2015).

Besides the beach sands in the coastal area, during the spreading process, the waves encounter underwater ridge, resulting in reduce of wave energy and unloading the carried sediments. The deposited sediments can be reworked into sand waves under the influences of wave and can be regarded as subaqueous beach sands. Similar sand bodies were found in S4 formation both in the central uplift region of Dongying Depression (Tian and Jiang 2009) or Huiming Depression (Zhang and Zhang 2009). Generally, these ridges are relatively far from the source area, may also form carbonate beach (Zhu et al. 1994; Yang et al. 2010).

1.2.2 Effect of the Wind on Carbonate Depositional System

The factors affecting carbonate sedimentation is very complex, including tectonism, biological, hydrological, and physical process. Among them, the wind and wave are important factors in controlling carbonate deposition.

1.2.2.1 The Influence of Wind and Waves on Carbonate Platform and Associated Sediment Types

(1) Influence of wind on carbonate platform type

During the development of carbonate platform, hydrodynamic changes can shape the slope and morphology of carbonate platform. In the case of increasing hydrodynamic power, the original low and flat platform slope become steep due to erosion and the grain size of sediment increases corresponding. On the contrary, as the water energy weakened, the steep slope of the original area becomes to accumulate finer grained sediments and then reduce the angle of slope.

Thus, original platform slope that created by tectonism can be modified by hydrodynamics and correspondingly the sediments deposited there can be also changed (Gu et al. 2009).

High-energy environment induced by strong wind and wave favor growth and development of reef organisms. The framework of the reef and rapid cementation of seawater can be resistant to waves and formed a high-energy coastal fringing reef. This kind of reef can be usually found at the turning point of the continental shelf and slope, forming a rimmed carbonates shelf. Compared with rimmed carbonate platform, rim-free platform or open platform often developed on the leeward side of the wave. When wave energy is relatively weak, the shelf margin lacks the grain beach facies or reef zone to form rims (Jiang 2010a).

(2) Influence of wind on sedimentary facies of carbonate platform

Water energy is the main factor controlling carbonate sedimentation. Shaw (1964) for the first time discussed the water energy of epicontinental sea environment and proposed the sedimentary differentiation of epicontinental sea carbonates depends mainly on the energy of the seawater. Waves, currents, and tides in the epicontinental sea are the main factors controlling the carbonate zonation. Irwin (1965) further proposed epicontinental sea depositional model and idea sequence of energy zones. From offshore to coastal area, the epicontinental sea can be divided into three zones, X, Y, and Z, according to the energy level (Fig. 1.14) (Liu and Zeng 1985).

X zone is characterized by low energy, below wave base and hundreds of kilometers wide. This zone is rarely disturbed, except bottom currents can affect sea floor. The sediments are mainly fine-grained with materials are delivered from the high-energy Y zone. The depositional rate is generally slow with thinner sediment thickness in this zone. Sediments are general in dark color and are characterized by typical parallel bedding.

Y zone is characterized by high-energy, tens of kilometers wide, active waves and tides are, sunny, rich in oxygen, and flourish of benthic algae. It often forms reefs or reef beaches. In the shore side of Y zone, due to the strong hydrodynamic various coarse-grained allochthonous carbonate particles are deposited, such as oolitic, and bioclastic and other autochthonous debris. Grains are mainly composed of sandy and gravel clastic with very few muds. Since bioclastic or oolitic are reworked and sorted by waves and currents in Y zone, the limestone formed there are characterized by cross-bedding and well-sorted particles.

Z zone is characterized by low-energy, hundreds of kilometers wide, shallow sea level that no more than a few meters and restricted water circulation. Z zone is mainly influenced by the tide and only slightly affected by the wave. Only storm can induce large waves to affect Z zone. Carbonate sediments of this zone are mainly low-energy marls, some of which are transported from the high-energy zone, and the others are the physical and chemical precipitation directly from seawater. Micritic limestone or laminar limestone and dolomite are major types of carbonate developed in this zone.

Wilson (1975) integrated a number of modern and ancient carbonate depositional models and the energy zone classification that based on the water energy with various parameters, including sea floor topography, tidal, wave, oxide interface, salinity, depth, water circulation, and climate conditions to establish a comprehensively standard carbonate depositional facies model. The marine carbonate can be divided into three facies zone and ten standard facies zone (Fig. 1.15). The basic framework is still composed of the low-energy, high-energy, low-energy zones. In the distal basinal facies zone, major facies zones are basinal facies, deepwater shelf facies, slope toe of platform facies and are located below wave base, which is characterized by low energy and corresponds to the low-energy X zone defined by Irwin (1965). In platform-margin facies zone, major facies zones are the slope of platform facies, platform-margin reef facies, platform-margin beach facies and are located above the wave base, which is characterized by high wave energy and corresponds to high energy Y zone defined by Irwin (1965). In platform facies zone, the open shelf platform facies, restricted platform, evaporate platform facies are major facies zones. The platform facies zone is located in the landside of platform margin and is commonly influenced by tide with little effect from the wave. This facies zone has relatively low water energy and corresponds to the low-energy Y zone defined by Irwin (1965). In some cases, part of open platform area may also have a higher hydrodynamic energy.

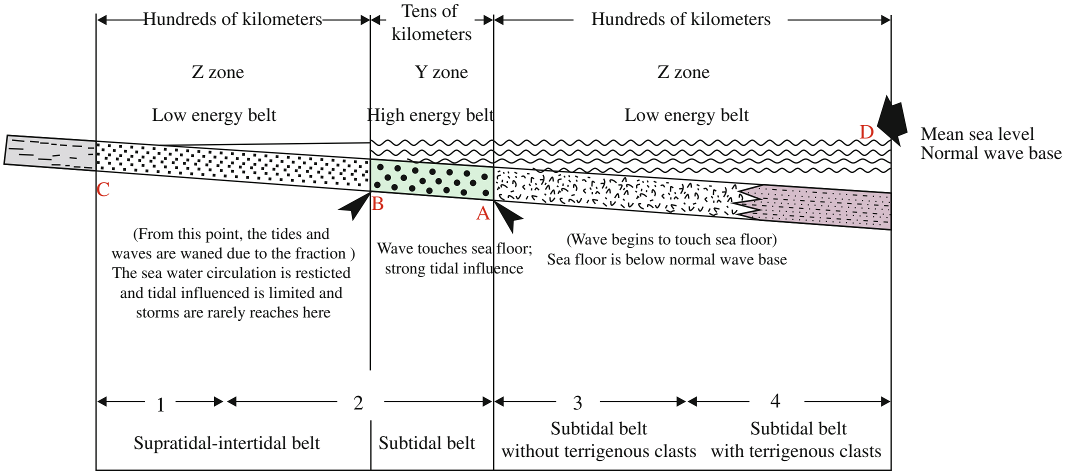

Fig. 1.14 Carbonate depositional patterns in epicontinental sea platform and ramp (modified from Liu and Zeng 1985; Flügel 2004). A-Wave base surface; B-Average low tide level; C-Mean sea level; D-Average high tidal level

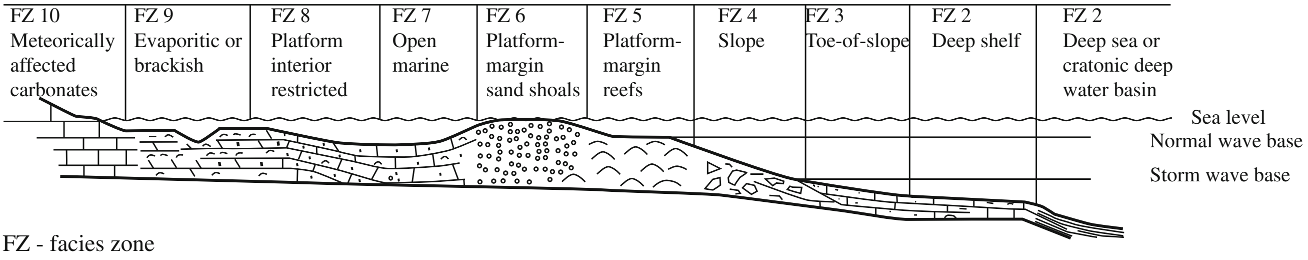

Fig. 1.15 Rimmed carbonate platform: modified from Wilson facies model (from Flügel 2004)

(3) Influence of wind on in situ growth of reef

Biological process is one of the important causes of carbonate deposition. Some organisms have ability to live in the high-energy water environment and build reef under high-energy waves and currents. In the high-energy zone, due to landward winds and tides, the waves begins to stir and cause seawater pressure changes. This make the raised seawater from bottom to be warm up and pressure released, leading to release of CO_2 and deposition of $CaCO_3$. Meanwhile this process also bring a lot of nutrients to shallow surface to enhance the growth and development reef. Therefore, fringing reef can be formed in the high-energy zone near shoreline, while the barrier reef is usually formed in shelf-margin (Chen et al. 2004). Because of the rapid cementation of biological framework and seawater, the reef can be resistant to waves and formed rimmed carbonate platform.

In addition, hydrodynamic conditions have a significant influence on the reef facies. Based on paleogeography and its corresponding hydrodynamic conditions and reef facies compositional characteristics, reef facies can be divided into three basic types (Fig. 1.16).

Type I is slope marl mound, located on the front edge of the continental shelf platform slope and composed of bioclastic marls. It has a linear shape in plane and has gentle slope angle, ranging from 2 to 25°.

Type II is ramp knoll reef, formed by linear reefs that build on the platform margin. It has a seaward gentle slope, ranging from a few degrees to 15 degrees. Due to the lack of strong wave action, it has lack organism that builds a massive framework, but the surface of the reef can be attached with other organisms.

Type III is steep slope skeleton reef, located in steep slopes fringe with a slope angle of 45° or even upright. This reef can grow to sea surface or wave stirring zone and mainly is composed of the biological framework.

(4) Influence of wind on sedimentary texture

Different water energy conditions will produce different sedimentary texture. Carbonate platform margin shoal depositional environment is a high-energy environment in platform-margin facies zone. It is located in the open shallow shelf with no barrier islands and vast algal mat, and thus the carbonate deposition is directly controlled by the marine and